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PORT HOPE TS - GROUNDING STUDIES

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Tests were conducted at Port Hope TS under simulated fault conditions in order to evaluate the grounding system performance at the station. Soil resistivity at the station was also tested. Models were developed to generalize the results. The measured and modelled station ground potential rise and touch and step potentials for a maximum HV fault current of 2.5 kA were found to be within safe limits. Preliminary calculations indicated that the station ground potential rise for an estimated LV fault current of 6.5 kA can exceed the allowable limit of 5 kV.

1.0 INTRODUCTION

Port Hope TS is an old 115-kV station located on the north side of Highway No 2, in the township of Port Hope. New 230-kV (to be initially operated at 115-kV) and 44-kV facilities are being added at the station and will be in service by end of 1988. The ground potential rise and touch and step potentials at the station were of concern, especially with the addition of the new facilities. Therefore, measurements were done under simulated fault conditions to confirm the adequacy of the grounding system performance of the station. The project was requested and funded by Design and Development Division - Transmission.

At the time of the tests, the high voltage facilities at the station included two 115-kV overhead lines and two transformers rated 50 MVA, 110/44/4 kV, Wye/Wye-Grounded/Delta. The station supplied loads through six 44-kV overhead feeders. The feeders leaving the station are without neutrals up to junctions where the poles carry underbuild neutrals. The new HV facilities include two additional similar transformers supplied

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from the existing 115-kV lines. There are no additional LV feeders planned for 1988 in-service, but a few existing feeders will be transferred to the new 44-kV area. The tests were conducted on August 24 and 25, 1988 with the new station ground grid completed and connected to the existing grid. The new HV and LV facilities were under construction at the time.

2.0 TEST PROCEDURE

Figure 1 shows a layout of Port Hope TS with respect to the grounding tests conducted at the station. A test current of about 4 A at 240 V, 68 Hz from a diesel generator installed in a Research Division van was injected between the station ground grid and a remote temporary ground rod using a dedicated test lead. The following measurements were made:

(a) Station ground potential rise between a remotely grounded Bell telephone remote pair and local station ground.

(b) A potential profile east of the station.

(c) Fence potentials and station touch and step potentials.

(d) Soil resistivity.

One of the three remote pairs of a Bell neutralizing transformer at the station was isolated from the primary winding for measurement in (a) above. The potentials (both magnitude and phase angle) were recorded with respect to 1.0∠0 A injected test current using an HP3582A network analyzer in conjunction with a differential amplifier. The analyzer was synchronized to the 68 Hz generator and is capable of rejecting 60 Hz noise. The reference current was measured using a Ritz clip-on 5 VA, 150/5 A current transformer with 0.66 Ω shunt. Fused gas-tube protectors were used to limit the potentials to local ground on the Bell pair and on the input wiring to the instrumentaion. A patch panel allowed the connection of the remotely grounded Bell pair to the instrumentation for a minimum duration to take a reading. All of the instrumentation was set up inside the test van and the van body was bonded to the main station ground using working grounds. Also heavy connections were made from the frame of the instrumentation to the station ground.

A soil resistivity survey using the Wenner method was conducted on a field east of the station property and a Megger DET-2 ground resistance tester was used to take the Wenner readings. A second survey south of the station entrance road did not give satisfactory data, probably due to the influence from adjacent LV distribution lines. Therefore, these were neglected and are not presented in this report. Adverse weather conditions did not permit any futher surveys.

A separate test was also conducted to check the practicality of a new procedure to monitor continuity of a ground grid. Here, a test current was injected between two points on the station ground grid and potentials were measured at selected points on the grid using the instrumentation described above. The details and results of this test will be analyzed and included in a separate report at a later date.

3.0 MEASURED RESULTS

3.1 Measured Soil Resistivity

The apparent soil resistivities calculated from the measured Wenner data (equation 7.1 of the Grounding Guide /1/) are given in Table 1 along with a fitted two-layer model parameters.

TABLE 1

PORT HOPE TS - SOIL RESISTIVITIES

Probe Spacing (m)	Apparent Resistivities (Ω.m)	
	Measured	Modelled
1	115.0	105.0
2	158.3	110.0
5	146.1	146.0
10	205.5	205.0
20	311.6	290.0
50	364.4	364.0
100	284.6	395.0

Fitted Two-Layer Model Parameters

ρ_1 = 100 Ω.m
d = 4 m
ρ_2 = 400 Ω.m

3.2 Measured Ground Potential Rise

Table 2 gives the measured ground potential rise along with the modelled values. For a maximum HV fault current of 2.5 kA, the maximum measured ground potential rise is about 2.7 kV.

The Bell remote pair, grounded about 7 km south of the station, was approximately at right angles to the current injection lead, allowing mutual coupling to be neglected.

For the potential profile measurements, the current and potential leads were oriented at an angle of about 60° and mutual coupling was probably present between them. However, as the calculated coupling (equation 4.81 of /3/) was found to be less than 1% of the measured result, the error was neglected. Also, the current injection to the remote current probe causes voltage rise at the remote potential probe due to earth's resistance. Correction factors were applied to the measured readings to compensate for this. The corrected measured profile readings were plotted against inverse distance which was then extrapolated to infinite distance at the origin to give ground potential rise. This assumes uniform soil resistivity and point current injection which should be accurate for larger distances. For potentials at closer distances, a disk geometry was assumed and a horizontal rescaling based on an inverse sine method was used /2/.

TABLE 2

PORT HOPE TS - GROUND POTENTIAL RISE (GPR)

GPR From	GPR (mV/A)
(1) Measured on Bell Pair	767.8/-14
(2) Measured Potential Profile	
a) Point Current Injection	1060.0/-10
b) Disk Geometry	1030.0/-10
(3) Modelled	
a) Test Condition	944.0/2
b) 1988 Final Stage (HV Fault)	753.0/-2

3.3 Measured Touch and Step Potentials

Touch and step potentials were measured at several locations and the worst case is presented in Table 3. A potential of about 47 mV/A was measured between the station fence and the station ground.

TABLE 3

PORT HOPE TS - TOUCH AND STEP POTENTIALS (mV/A)

	Measured	Modelled	
		*Test Condition	*HV Fault (Final Stage)
Fence Touch Potential			
a) Outside	6.3/-33	9.4/2	72.9/-2
b) Inside	8.4/-33	-	-
Station Touch Potential (Mesh Voltage)	26.4/-5	76.5/2	59.0/-2
Station Step Potential	32.8/4	34.7/2	28.5/-2

*See Section 4.0 for details.

4.0 MODELLED RESULTS

The station grounding system performance was calculated for the test condition in order to validate the model. Based on the model, the station grounding system performance was estimated for the 1988 final stage. Station facilities under these two conditions are explained in section 1. For the test condition, the station fence was assumed to be isolated from the station ground and this is indicated by the measurements. However, calculations for the final stage are based on an interconnected fence according to the station drawings. Appendix A summarizes the various formulas used in the calculation, other than those given in the references.

4.1 Soil Resistivity

The measured soil resistivity data resulted in a two-layer model using the method given in Appendix D of the Grounding Guide /1/. An equivalent resistivity of 240 Ω.m was derived for an estimated equivalent station radius of 74 m.

4.2 Isolated Station Ground Resistance

For the test condition with an isolated station fence, a station ground resistance R_g of 1.08 Ω was calculated based on an equivalent station radius of 61 m and 2600 m of buried ground conductors (equation 3.3 of the Grounding Guide /1/). Based on an equivalent station radius of 74 m and 3300 m of buried ground conductors for the 1988 final stage, assuming that the fence would be connected to the grid as indicated in the station drawings, the calculated R_g is 0.88 Ω.

4.3 Conductive Equivalent Circuit

Figure 2 shows the conductive equivalent circuit with respect to fault current distribution at the station. The distribution feeders leaving the station have no neutrals connected to the station ground grid and hence were neglected in the models. Preliminary calculations indicated that the distribution transformer neutral impedance (leakage + neutral grounding reactor + load) does not significantly reduce the interconnected station ground impedance and was neglected in the models for simplicity.

For the 42 mm^2 (5/16") steel skywire of the HV double-circuit line, the conductor earth return self and mutual impedances, calculated using Carson's simplified formulas, are 5.5/30 Ω/km and 0.40/82 Ω/km respectively. Based on an estimated tower footing resistance of 30 Ω and a span length of 320 m, the lumped conductive skywire self impedance Z_c was calculated as 7.27/15 Ω.

4.4 Modelled Current Splits

The equivalent circuit in Figure 2 was solved for an injected fault current of 1.0/0 A for the test condition and the calculated current splits are given in Table 4. The interconnected station ground impedances are 0.94/2 Ω for the test condition and 0.79/2 Ω for the final stage.

TABLE 4

MODELLED CURRENT SPLITS (mV/A)

	Test Condition	HV Station Fault (Final Stage)
Station Ground	0.874/2	0.856/-2
Skywire	0.130/-13	0.147/11

4.5 Modelled Ground Potential Rise

The station ground potential rise was calculated as $I_g R_g$, where I_g is the station ground current split and R_g is the isolated station ground resistance. Table 2 compares the modelled value with the measured results.

4.6 Modelled Touch and Step Potentials

The calculated touch and step potentials are given in Table 3 along with the measured results. The fence outside touch potentials were calculated using equations 3.11 and 3.10 of the Grounding Guide /1/, for the test condition (fence isolated from the station grid) and

for the 1988 final stage (fence tied to the station grid) respectively. Here, a distance of 10 m between the fence and the grid and an average spacing of 10 m between parallel grid conductors were assumed. The station mesh and step voltages were calculated using equations 3.6 of the Grounding guide /1/ and 73 of the IEEE Guide 80 /4/, respectively.

4.7 Tolerable Limits of Touch and Step Voltages

The tolerable touch and step voltage limits for the station were calculated for general population standing on crushed stone using equations 2.4 and 2.2 of the Grounding Guide /1/, respectively. Assuming a depth of 80 mm of crushed stone and a fault duration of 0.5 sec, the calculated touch and step voltage limits are 575 V and 1857 V, respectively.

4.8 Modelled Results for a HV Station Fault

For a HV station fault, only the conductive component of the fault current enters the station grounding system due to shielding of the skywire. This conductive component of the fault current was derived as SI_f where S is the shielding factor calculated from the skywire self and mutual impedances. The inductive component of the skywire current split is $(1\text{-}SI_f)$. The calculated shielding factor is $0.957\angle\underline{-4}$.

Therefore, the equivalent circuit in Figure 2 was solved for an injected fault current of $Sx1.0\angle\underline{0}$ A for a HV station fault and the calculated current splits are given in Table 4. Note that the total skywire split is the sum of the conductive and inductive components. The station ground potential rise calculated as $I_g R_g$ (see Table 2) is about 1.9 kV for a maximum HV fault current of 2.5 kA.

For the above fault current of 2.5 kA, the calculated fence outside touch potential is about 182 V and the station mesh and step potentials are approximately 163 V and 78 V, respectively.

4.9 Estimated Results for a LV Fault

A LV fault at the station will not cause any ground rise as the fault current circulates within the station without entering the ground. Preliminary calculations were done to estimate the station grounding system performance in the event of a LV ground fault outside the station. With no bonding of the distribution feeder neutrals to the station ground grid, there is no return current in the feeder neutrals. Also neglecting the ground resistance at the fault location and the transformer neutral impedance, to be conservative, the entire fault current returns through the station ground and the skywire. The corresponding estimated station grounding system performance for 1988 final stage would be,

station ground potential rise	$-785.0\angle\underline{2}$ mV/A
station ground current split	$-0.895\angle\underline{2}$ A
fence outside touch voltage	$-76.3\angle\underline{2}$ mV/A
station mesh voltage	$-61.6\angle\underline{2}$ mV/A
station step voltage	$-29.7\angle\underline{2}$ mV/A

According to a fault study by System Planning Division, the 1988 maximum fault level is about 9.8 kA for a 44-kV line-to-ground fault at the station. For a fault just outside the station, such as a broken phase conductor lying on the ground, a fault impedance of about 6 Ω was estimated for the phase conductor (336.4 kcmil ACSR) based on the ground rod formula (equation 3.4 of the Grounding Guide /1/). Here, a span of 50 m and a surface layer resistivity of 100 Ω.m were assumed. Neglecting the source impedance, this would result in a fault current of about 4.2 kA. Alternately, if the fault occurs at a junction outside the station on a pole carrying under-build neutrals, the total fault impedance would include the source impedance, the earth return self-impedance of the phase conductor and the chain impedance of the feeder neutral conductor. For a 44-kV line-to-ground fault close to the station at Gage Creek Jct, which is about 600 m north of the station, the net fault impedance and the fault current would be about 4 Ω and 6.5 kA respectively. Here, distribution taps to farmers at 500 m spacings with 107 mm^2 (4/0 AWG) ACSR ground wires and a ground resistance of 5 Ω at each house were assumed. The estimated station ground potential rise for the above LV fault current of 6.5 kA would be about 5.1 kV and the fence outside touch potential and station touch and step potentials would be approximately 500 V, 400 V and 193 V, respectively.

5.0 DISCUSSION OF RESULTS

a) The soil resistivity survey near the station indicates a multi-layer soil structure and an average-fitted two-layer soil model was considered adequate for the station grounding system study. The equivalent resistivity of 240 Ω.m derived from the measured Wenner data compares reasonably with a resistivity of about 300 Ω.m estimated from the measured potential profile data.

b) The modelled ground potential rise (GPR) is approximately an average of the two measured results. The GPR from the potential profile measurements may be conservative due to neglecting the mutual coupling between the current injection and potential leads. The considerably lower value measured on the Bell remote pair compared to that from the profile data is probably caused by induction due to current splits in the adjacent two loaded pairs in the cable which are connected to the station ground through the neutralizing transformer primary winding. Since enough data such as the above current split or circuit impedance was not readily available, no attempt was made to estimate a correction factor to compensate for this measurement error.

   For a maximum HV fault current of 2.5 kA, the modelled and the maximum measured station GPR are under the recommended limit of 3 kV.

c) With no bonding of the distribution feeder neutrals to the station ground grid, fault currents entering the station grounding system split mainly between the station ground and the skywire. Due to the high impedance and poor shielding of the skywire almost 90% of the fault current enters the station ground. Preliminary calculations indicate that bonding between the under-build neutrals and the station grid could reduce the ground current split by about 45%. Significant improvement

can also be obtained by reducing the skywire impedance using larger size, double skywires, aluminum-clad instead of steel etc.

d) The measured and modelled touch and step voltages are all well within the tolerable limits calculated for the station with a surface layer of crushed stone. Without the crushed stone, the touch voltages could have approached a tolerable limit of 190 V calculated for the bare soil at the station. The equations used in calculating the touch and step voltages apply to uniform ground grid. For the irregular grid geometry at the station, the various parameters were estimated and therefore, the modelled values may not be accurate.

e) The measured fence touch potential is lower compared to the modelled value, probably due to the gradient control conductor around the fence. For the 1988 final stage, the modelled fence touch voltage of about 182 V to the public outside is well under the tolerable limit of 575 V with the crushed stone and will be further reduced with the gradient control conductor.

f) The potential of about 47 mV/A (about 5% of the GPR) measured between the station fence and the grid and also the considerably lower measured fence touch voltage compared to the GPR indicate that the fence may not be connected to the station ground grid. Therefore, the modelled parameters for the test condition are based on an isolated fence and compare reasonably well with the measured results. However, the calculations for the 1988 final stage were done with the fence connected to the grid as indicated in the station drawings. On the other hand, if the fence is isolated from the grid, preliminary calculations indicate that the station GPR could increase by about 20% and the fence touch voltage would be considerably reduced.

g) For a LV ground fault outside the station, the calculated station ground potential rise of about 5.1 kV for an estimated fault current of 6.5 kA exceeds the allowable limit of 5 kV. But the model is based on conservative assumptions. Here, the fence was assumed to be connected to the station grid. For an isolated fence, the corresponding station GPR would be increased further. The estimated touch and step potentials for the above LV fault current are under the tolerable limits.

6.0 CONCLUSIONS

a) Wenner resistivity measurements at Port Hope TS indicate a multi-layer earth structure at the station. A two-layer interpretation of the data yielded the following parameters: ρ_1=100 Ω.m, d=4 m, ρ_2=400 Ω.m. The equivalent soil resistivity at the station for an estimated station radius of 74 m is about 240 Ω.m based on the two-layer model.

b) The isolated station ground resistance of 0.88 Ω was estimated from the grid geometry with the station fence connected to the station ground grid. The calculated interconnected station ground impedance is about 0.79/2 Ω.

c) Measurements indicated that the station fence may not be bonded to the station ground grid. However, the station grounding system performance for 1988 final stage was calculated for an interconnected fence as per the station drawings.

d) For an injected fault current of 2.5 kA, the maximum measured station ground potential rise (GPR) is about 2.7 kV from the potential profile data and the corresponding modelled value is about 2.4 kV for the test condition. Here, the station fence was assumed to be isolated from the station ground grid as noticed during measurements. For a maximum HV station fault current of 2.5 kA, the modelled GPR is about 1.9 kV due to the skywire shielding and a reduced station ground resistance with the station fence connected to the grid as per the station drawings. The measured and modelled GPR are under the recommended limit of 3 kV.

Preliminary calculation based on conservative assumptions gave a GPR of about 785/2 mV/A for a LV fault outside the station. This is about 5.1 kV for an estimated fault current of 6.5 kA and exceeds the allowable limit of 5 kV. With an isolated station fence the station GPR would be increased further.

e) With no bonding of distribution feeder neutrals to the station ground and due to the high impedance and poor shielding of the steel skywire, almost 90% of the fault current enters the station grid, as calculated. Preliminary calculations indicated that a significant reduction (about 45%) in the ground current split could be achieved by bonding of under-build neutrals to the station grid.

f) The tolerable touch and step potentials for the station were calculated as 575 V and 1857 V for general public standing on crushed stone.

g) The measured and modelled station fence touch potentials are well under the tolerable touch voltage limit. For a maximum HV fault current of 2.5 kA, the modelled fence touch potential to the public outside is about 182 V (72.9/-2 mV/A), assuming that the fence is connected to the station grid, and should be further reduced due to the gradient control conductor.

h) The measured and modelled station touch (mesh) and step potentials for the above HV and LV fault currents are well under the tolerable limits.

7.0 ACKNOWLEDGEMENTS

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3. E.D. Sunde, Earth Conduction Effects in Transmission Systems, Published by D. Van Nostrand Company, Inc.

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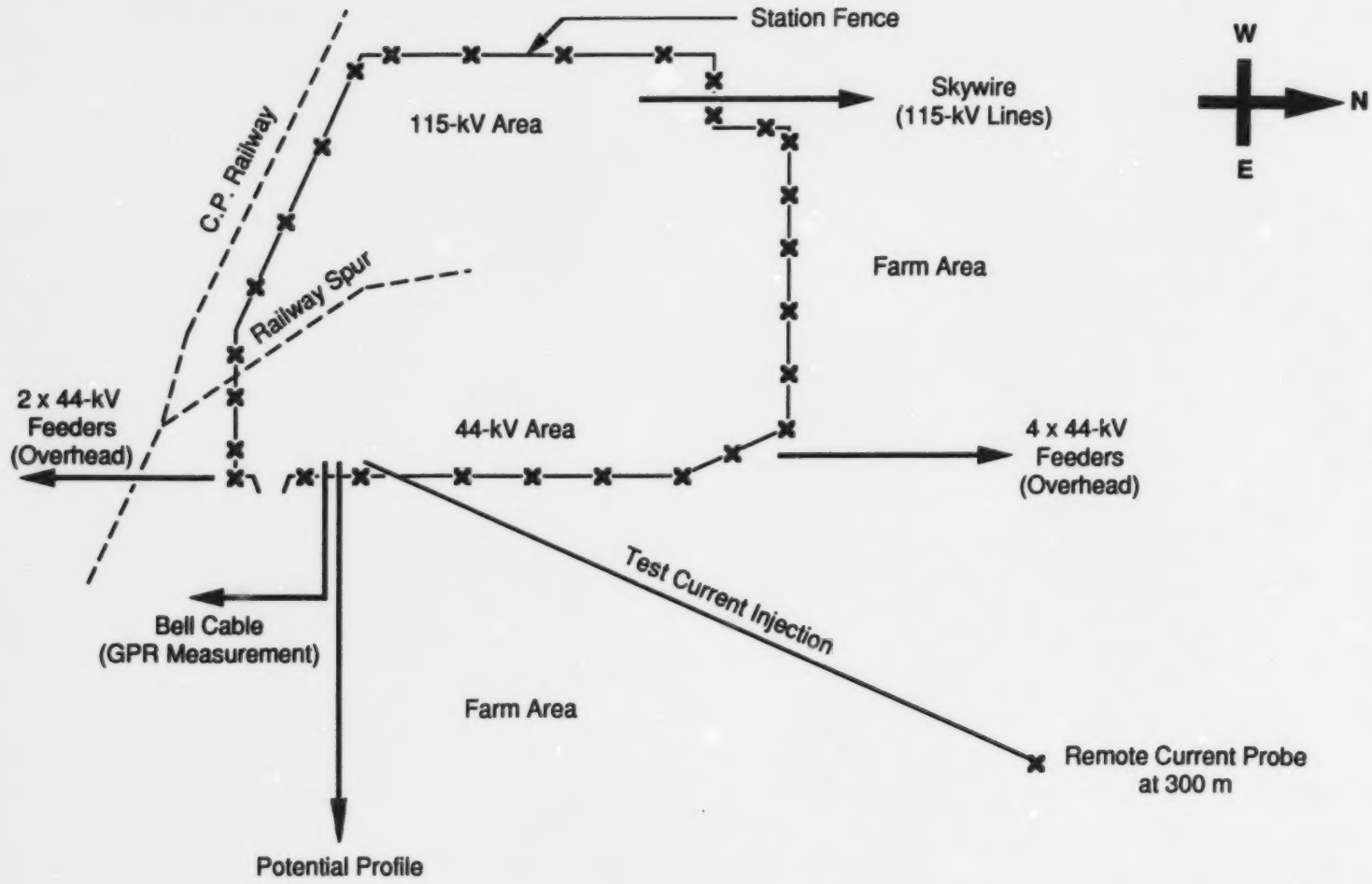

FIGURE 1

PORT HOPE TS
LAYOUT WITH RESPECT TO GROUNDING TESTS

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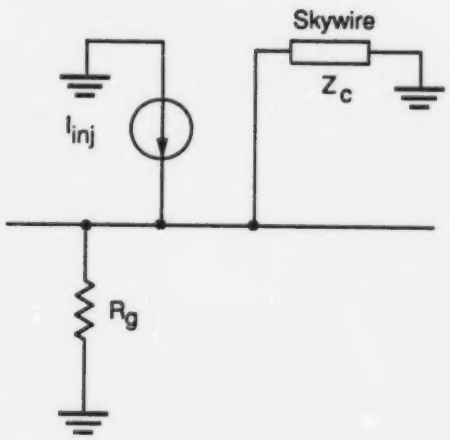

FIGURE 2

PORT HOPE TS
CONDUCTIVE EQUIVALENT CIRCUIT

APPENDIX A

SUMMARY OF FORMULAS USED IN GROUNDING CALCULATIONS

1. Conductor Earth Return Self Impedance, Z_s

$$Z_s = R_s + jX_s \quad (\Omega/km) \qquad (1)$$

$$R_s = 0.059 + R_{ac} \quad (\Omega/km) \qquad (2)$$

$$X_s = 0.0377 \ln (8440 \rho_s / GMR^2) \qquad (3)$$

Where, R_{ac} = conductor ac resistance (Ω/km)
ρ_s = soil resistivity (Ω.m)
GMR = conductor geometric mean radius (m)

For pipes or shields, R_{ac} and X_{ac} (conductor internal reactance added to X_s) are calculated as shown in Ontario Hydro Research report No. 83-433-K, dated November 7, 1983, by E.P. Dick.

2. Conductor Earth Return Mutual Impedance, Z_m

$$Z_m = R_m + jX_m \quad (\Omega/km) \qquad (4)$$

$$R_m = 0.0377 \tan^{-1} (8440 \rho_s / GMD^2) \qquad (5)$$

$$X_m = 0.0377 \ln [(8440 \rho_s / GMD^2) + 1] \quad (\Omega/km) \qquad (6)$$

Where, ρ_s = soil resistivity (Ω.m)
GMD = geometric mean diastance between conductors (m)

3. Tower Footing Resistance, R_t

$$R_t = \rho_s / 2\pi [(1/r) + (2.707/w)] \quad (\Omega) \qquad (7)$$

Where, ρ_s = soil resistivity (Ω.m)
r = equivalent footing radius (m)
w = footing spacing (m)

4. Chain Impedance of Skywires, Z_c

$$Z_c = \sqrt{Z_s \, l \, R_t} \quad (\Omega) \qquad (8)$$

Where, Z_s = conductor earth return self impedance (Ω/km)
l = span length (km)
R_t = tower footing resistance (Ω)

5. Skywire Shielding Factor, S

$$S = 1 - (Z_m / Z_s) \qquad (9)$$

Where, Z_m = conductor earth return mutual impedance (Ω/km)
Z_s = conductor earth return self impedance (Ω/km)

6. Station Earth Potential to Remote Ground, $V_{(x)}$

For disk-like electrode in uniform soil,

$$V_{(x)} = (\rho_s \, I_g / 2\pi r) \sin^{-1} (r/x) \quad (V) \qquad (10)$$

For point current injection in uniform soil,

$$V_{(x)} = \rho_s \, I_g / 2\pi x \quad (V) \qquad (11)$$

Where, ρ_s = soil resistivity (Ω.m)
I_g = ground current (A)
r = station radius (m)
x = distance from station centre (m)